

Short Course on Experimental Dynamic Substructuring

Module #9: Closing Remarks



THE UNIVERSITY
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Short Course Notes For:

January 23, 2016, IMAC, Orlando, Florida

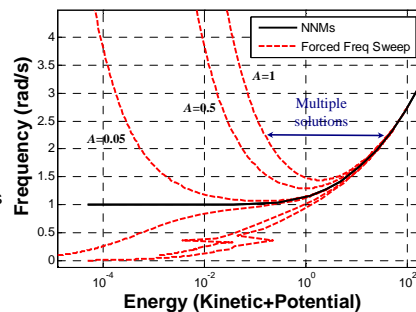
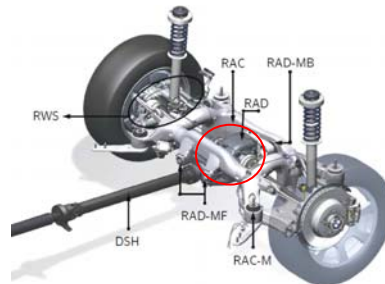
Other Topics of Interest

Transfer Path Analysis

- Used to characterize vibration sources when the forces causing the motion are unknown.
- Closely related to the theory covered here!
- See references for a starting point.

Nonlinear Substructuring

- Nonlinear normal mode (NNM) theory
 - Frequency-energy dependence
 - Relationship to free response, forced response
 - Internal resonance and modal interactions
- Substructuring with strongly nonlinear models
 - Modal approaches
 - Substructuring of Reduced Order Models (ROMs)
- NL Substructuring of weakly nonlinear systems for structures with joints

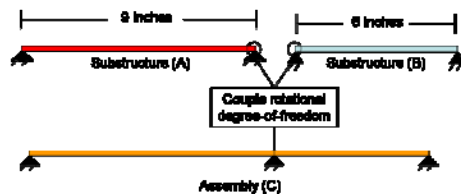


References and bibliography for TPA *(non exhaustive!)*

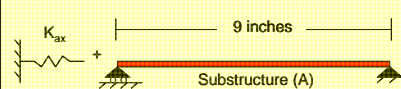
- 1 D. de Klerk. *Dynamic Response Characterization of Complex Systems through Operational Identification and Dynamic Substructuring: An application to gear noise propagation in the automotive industry*. PhD thesis, Delft University of Technology, Delft, The Netherlands, March 2009.
- 2 G. van Schothorst, A. Boogaard, T. van der Poel, and D. Rixen. Analysis of ground vibration transmission in high precision equipment by frequency based substructuring. In P. S. et al., editor, *International Conference on Noise and Vibration Engineering, ISMA*, number 915, KUL, Leuven, Belgium, 17-19 September 2012.
- 3 D. J. Rixen, A. Boogaard, M. V. van der Seijs, G. van Schothorst, and T. van der Poel. Source description in vibration transmission between substructures: blocked forces and free velocities. *Journal of Sound and vibration*, (submitted), 2014.
- 4 A. Moorhouse, A. Elliott, T. Evans, In situ measurement of the blocked force of structure-borne sound sources, *Journal of Sound and Vibration* 325 (4-5) (2009) 679 – 685. doi:<http://dx.doi.org/10.1016/j.jsv.2009.04.035>. URL <http://www.sciencedirect.com/science/article/pii/S0022460X09003794>

Kuether & Allen presented several studies involving substructuring with nonlinear reduced order models

- Coupling two geometrically nonlinear beams at shared rotational DOF
 - Free-Interface modes
 - Fixed-interface plus constraint modes

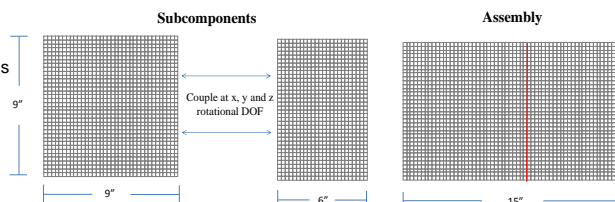


- Coupling geometrically nonlinear beam to axial spring element
 - Fixed-interface plus constraint modes

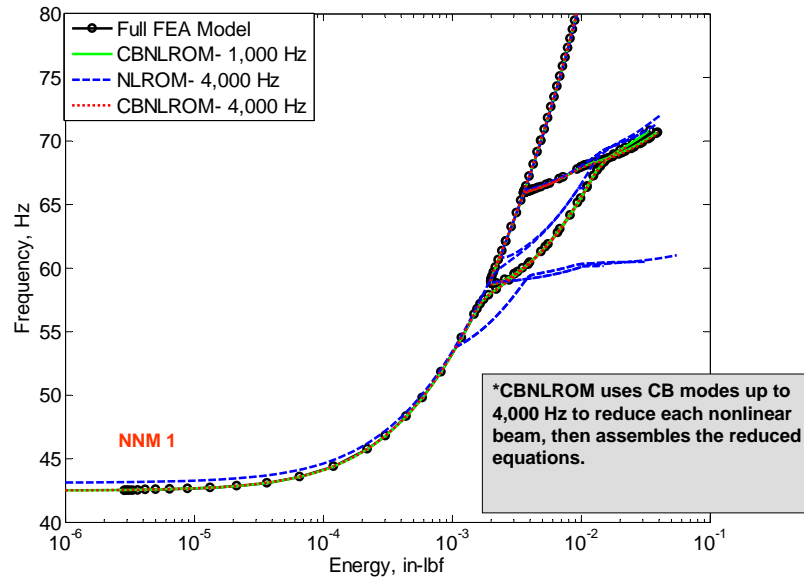


See IMAC Paper

- Coupling two geometrically nonlinear plates at continuous interface
 - Fixed-interface plus characteristic constraint modes



Nonlinear Substructuring Results



References

Rigorous approach based on nonlinear Reduced Order Models.

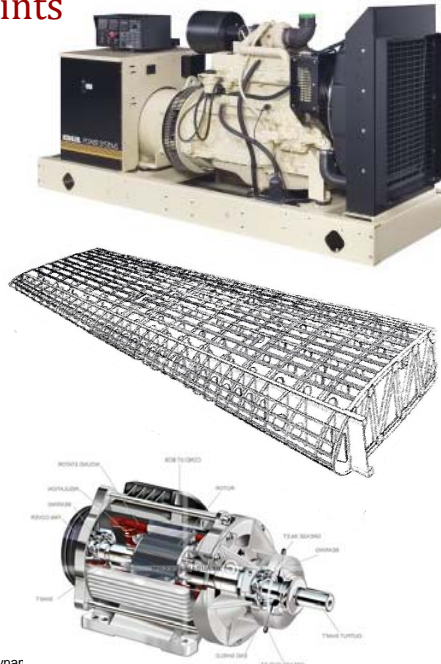
- R. J. Kuether and M. S. Allen, "Nonlinear Modal Substructuring of Systems with Geometric Nonlinearities" in *54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* Boston, MA, 2013
- R. J. Kuether, M. S. Allen, and J. J. Hollkamp, "Modal Substructuring for Geometrically Nonlinear Finite Element Models," *AIAA Journal*, (Accepted Aug. 2015).
- R. J. Kuether and M. S. Allen, "Substructuring with Nonlinear Reduced Order Models and Interface Reduction with Characteristic Constraint Modes," in *55th AIAA/ASME/ASCE/AHS/SC Structures, Structural Dynamics, and Materials Conference* National Harbor, Maryland, 2014

Related Papers at IMAC 2016:

- J. D. Schoneman and M. S. Allen, "Investigating Nonlinear Modal Energy Transfer in a Random Load Environment," in 34th International Modal Analysis Conference (IMAC XXXIV) Orlando, Florida, 2016
 - Session 17 (Tuesday Morning), 11:50 AM, Paper # 233
- C. VanDamme and M. S. Allen, "Using NNMs to Evaluate Reduced Order Models of Curved Beam," in 34th International Modal Analysis Conference (IMAC XXXIV) Orlando, Florida, 2016
 - Session 55 (Thursday Afternoon), 2:00 PM Paper# 212

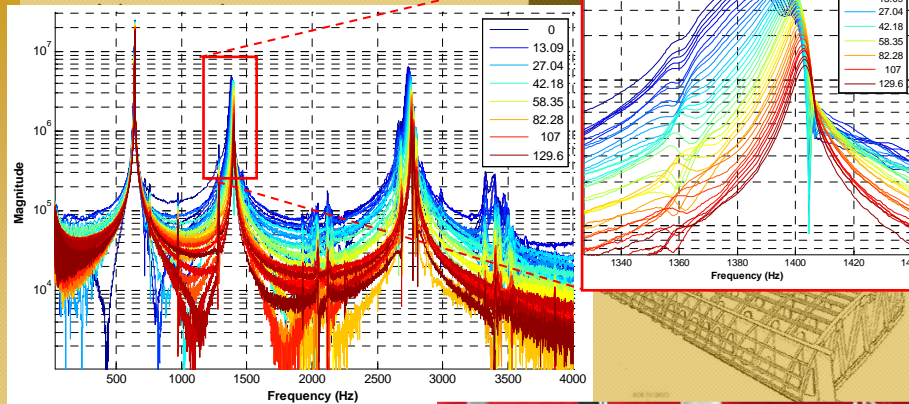
Nonlinearity due to Joints

- Joints are the most common source of nonlinearity in built up structures.
- Much of the damping in many built up structures comes from friction in the joints.
- Joints tend to cause relatively weak stiffness nonlinearities (natural frequencies may shift by a few percent or less).
- However, they can cause the damping to change significantly.
 - Factor of 2-4 changes in damping have been observed!



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Nonlinearity due to Joints



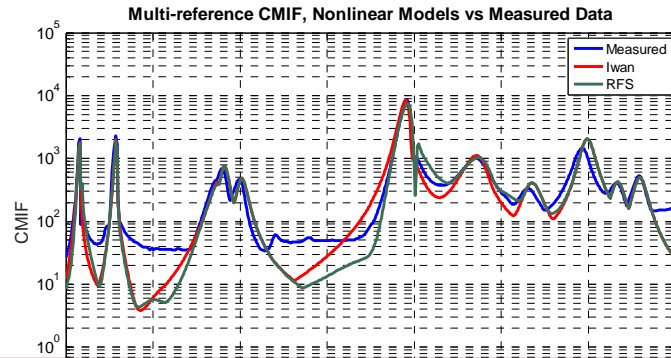
significantly.

- Factor of 2-4 changes in damping have been observed!



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So far, weakly nonlinear models seem to work quite well for this type of structure.



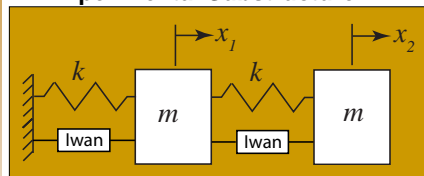
For more detail, see:

R. L. Mayes, B. R. Pacini, and D. R. Roettgen, "A Modal Model to Simulate Typical Structural Dynamic Nonlinearity," in 34th International Modal Analysis Conference (IMAC XXXIV) Orlando, Florida, 2016

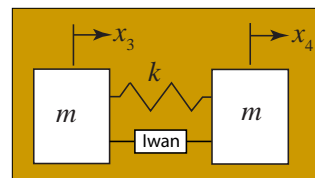
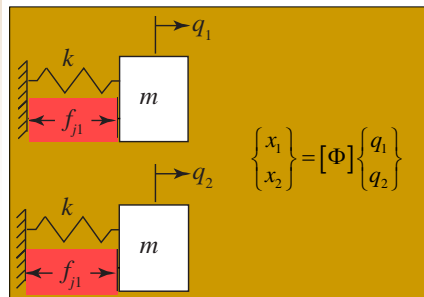
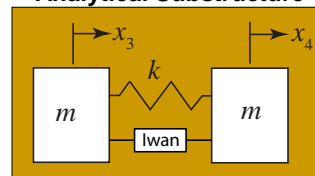
Session 21 (Tuesday Early Morning), 9:00 AM, Paper #121

Substructuring can be adapted to couple nonlinear modal models (instead of physical models).

Experimental Substructure

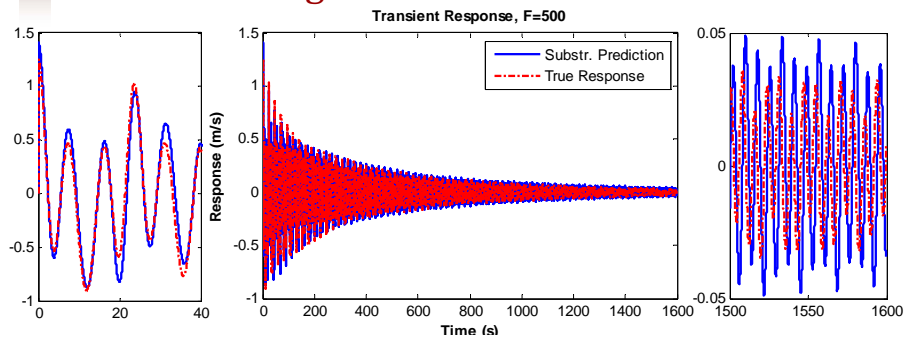


Analytical Substructure



- Again the linear systems are assembled and the joints are replaced with joint forces, now between each modal DOF and ground.

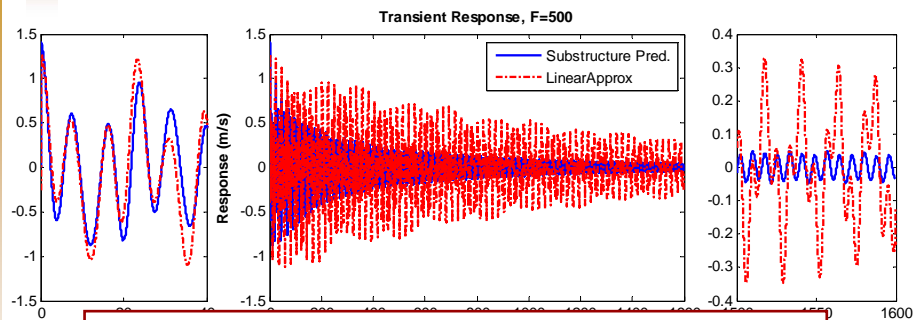
Substructuring Predictions: Nonlinear



- Response of Mass 5 shown: Modal Substructuring Prediction and True Response computed by directly assembling EOM.
 - Damping seems to be correct over a range of response amplitude.
 - The responses de-phase after a long time, but frequency is still quite accurate.

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Comparison: Nonlinear & Linear Models, $F_0=500$



For the whole story, see:

- M. S. Allen, D. R. Roettgen, D. C. Kammer, and R. L. Mayes, "Experimental Modal Substructuring with Nonlinear Modal Iwan Models to Capture Nonlinear Subcomponent Damping," in *34th International Modal Analysis Conference (IMAC XXXIV)* Orlando, Florida, 2016.

Session 21 (Tuesday Early Morning), 9:20 AM, Paper #334

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Concluding Remarks

- While many of the classical concepts involved in substructuring have been around for decades, experimental-analytical substructuring is an area ripe for discovery!
 - Better experimental methods are still needed
 - Extensions to weakly and strongly nonlinear systems
 - Transfer Path Analysis (TPA) and force reconstruction
 - etc...
- We hope you have enjoyed the course and welcome any feedback that you may have!